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Can four-fermion contact interactions at one-loop explain the new atomic parity violation results?

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Abstract

We investigate the possibility that four-fermion contact interactions give rise to the observed deviation from the Standard Model prediction for the weak charge of Cesium, through one-loop contributions. We show that the presence of loops involving the third generation quarks can explain such deviation.

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I. INTRODUCTION

For the last fifty years, most of the activity on particle physics relied on the use of large particle accelerators. These devices, allowing the scientists to break matter down to its most elementary constituents, have been fundamental in helping particle physicist to reveal the secrets of matter. However, besides these high-energy experiments, low-energy experiments were also carried out, giving very important contributions, like the confirmation of parity violation in weak interactions. In fact, low-energy experiments always played a important role in particle physics. But now, the perspectives are that during the first decade of the next century the importance of low-energy experiments must increase significantly. Until LHC collects enough data, the measurement of anomalous magnetic moment of muon [1] and atomic parity violation (APV) in heavy atoms [2] are going to be a source of significant new results [3].

The measurement of APV in heavy atoms is one of the most important and ambitious low energy experiments being carried out. The aim is to achieve a 0.1% accuracy in the measurement of the weak charge of Cesium in the next few years. Recently a new step was given in this direction, the weak charge of Cesium was reported to 0.6% [4],

$$Q_W(^{133}_{55}Cs) = -72.06 \pm (0.28)_{exp} \pm (0.34)_{theor}, \quad (1)$$

We must compare this result with the prediction of the Standard Model (SM). Including radiative corrections, it is conveniently expressed in terms of the oblique parameters as,

$$Q_W^{SM} = -72.72 \pm 0.13 - 102\epsilon_3^{rad}, \quad (2)$$

were the hadronic-loop uncertainty has been included. The value of ϵ_3^{rad} depends on the top quark and Higgs boson mass. For $m_{top} = 175$ GeV we have [5]

$$\epsilon_3^{rad} = 5.110 \times 10^{-3} \quad (M_H = 100\text{GeV}) \quad (3)$$

$$\epsilon_3^{rad} = 6.115 \times 10^{-3} \quad (M_H = 300\text{GeV}). \quad (4)$$

In the calculations hereafter we assume the ϵ_3^{rad} given in Eq. (3). It is important to stress that our final conclusions are not going to depend in a significant way of ϵ_3^{rad} dependence on the Higgs mass. Comparing the theoretical prediction and the experimental value of Q_W we conclude that

$$Q_W^{exp} - Q_W^{SM} = 1.18 \pm 0.46, \quad (5)$$

This result implies that the SM prediction and the experimental result are 2.6σ apart. From Eq. (5) we see that the allowed range of variation for the total new physics contribution to the weak charge, ΔQ_W , is

$$0.28 \leq \Delta Q_W \leq 2.08. \quad (6)$$

at 95% CL. This result is quite interesting. In fact, as noted in Ref. [5], it can be shown that taking seriously the new result for $Q_W(^{133}_{55}Cs)$ we can exclude the SM at 99% CL.

In Ref. [4] the authors see no justification to believe that such discrepancy originates from some experimental or theoretical mistake. They suggest instead that the new value of

Q_W may have been originated from the presence of some kind of new physics beyond the SM. This possibility has already been explored up to some extent in Refs. [5,6], were it is shown that the observed deviation in Q_W can be explained by the presence of a new neutral gauge boson. Leptoquarks and certain four-fermion contact interactions can also account for the present discrepancy [5]. We point out that all these new contributions are at tree-level. No analysis was done considering the effects of new physics through one-loop effects. With the intention of filling partially this gap we analyze here if four-fermion contact interactions that do not contribute at tree-level, can lead to sizeable contributions to Q_W , through one-loop level diagrams.

II. ONE-LOOP EFFECTS OF FOUR-FERMION CONTACT INTERACTIONS

Presently, the bounds on new physics are such that the new particles, if they exist, must be very heavy. Under these conditions the effects of these new particles intermediating interactions involving four-fermions can be approximated as contact interactions. In the specific case of APV, the contact interactions that can contribute at tree-level have the form $g(\bar{e}\Gamma e)(\bar{q}\Gamma q)$, where g is the coupling constant, Γ denotes an adequate combination of gamma matrices, e is the spinor for the electron in the electrospHERE, and q corresponds to the spinor of a quark in the atomic nucleus. When we want to deal with one-loop effects we can consider more general expressions for the four-fermion interactions. We can consider scalar, vectorial, and tensorial interactions involving not only two leptons and two quarks, as shown above, but also interactions involving only quarks, or only leptons. In general, these interactions can be expressed in terms of the following Lagrangians [7]:

$$\mathcal{L}_{\text{scalar}} = \eta \frac{g^2}{\Lambda^2} [\bar{\psi}_m (V_S^m - iA_S^m \gamma_5) \psi_m] [\bar{\psi}_n (V_S^n - iA_S^n \gamma_5) \psi_n] , \quad (7a)$$

$$\mathcal{L}_{\text{vector}} = \eta \frac{g^2}{\Lambda^2} [\bar{\psi}_m \gamma^\mu (V_V^m - A_V^m \gamma_5) \psi_m] [\bar{\psi}_n \gamma_\mu (V_V^n - A_V^n \gamma_5) \psi_n] , \quad (7b)$$

$$\mathcal{L}_{\text{tensor}} = \eta \frac{g^2}{\Lambda^2} [\bar{\psi}_m \sigma^{\mu\nu} (V_T^m - iA_T^m \gamma_5) \psi_m] [\bar{\psi}_n \sigma_{\mu\nu} (V_T^n - iA_T^n \gamma_5) \psi_n] , \quad (7c)$$

where Λ is the energy scale of the effective interaction, $V_{S,V,T}^{m,n}$ and $A_{S,V,T}^{m,n}$ are real constants with m and n being the lepton and quark flavors, and g is the coupling constant which can depend on the fermion flavors. The parameter η can assume the values ± 1 in order to allow a constructive or destructive interference with the standard contribution for a given process. Here we have assumed the most general four-fermion interactions, in which the new physics present at high energies must respect only a $U(1)$ symmetry. Such a choice allow us to parametrize not only interactions that respect the $SU(2) \times U(1)$ symmetry of the SM, but also, and more accurately, the interesting case of extensions based on extra $U(1)$ symmetries.

The tensorial and scalar interactions are so severely constrained by many experiments [7,8] that we will simply disregard them hereafter. We consider only the one-loop effects of the vectorial four-fermion contact interaction, Eq. (7b). The diagrams that contribute to Q_W

are represented in Figs. 1 and 2. In these diagrams the fermion f can be either an electron of the electrosphere or a quark of the nucleus, and we allow f' to be any fermion present in the SM. The only restriction, obviously, is that the four-fermion interaction cannot have any significant contribution at tree-level. This implies that we do not consider interactions like $\bar{e}\gamma e\bar{q}\gamma q$ ($q = u, d$ quarks). The effect of the two diagrams is to modify the form factors F_i , $i = v, a$ in the following Z boson current

$$J^\mu = e \bar{u}_f(p_1) (F_v \gamma^\mu + F_a \gamma^\mu \gamma_5) v_f(p_2). \quad (8)$$

The form factors are functions of Q^2 , with $Q = p_1 + p_2$. F_v and F_a are present at tree-level in the SM

$$F_v^{\text{tree}} \equiv G_V = \frac{1}{2 s_W c_W} (T_3^f - 2 Q_f s_W^2), \quad F_a^{\text{tree}} \equiv -G_A = -\frac{1}{2 s_W c_W} T_3^f, \quad (9)$$

where $s_W (c_W) = \sin (\cos) \theta_W$, T_3^f and is the third component of the fermion weak isospin. The contributions of the diagrams presented in Figs. 1 and 2 to F_v and F_a have already been evaluated in Ref. [7], and are similar to the results of Refs. [9,10].

The contribution of the interaction depicted in Eq. (7b) to the s -channel is

$$\begin{aligned} \delta F_v &= \eta \frac{g^2}{48\pi^2 \Lambda^2} \left\{ \left[6G_A M_{f'}^2 - (G_V + G_A) Q^2 \right] (V_V^l + A_V^l)(V_V^u + A_V^u) \right. \\ &\quad \left. - \left[6G_A M_{f'}^2 + (G_V - G_A) Q^2 \right] (V_V^l - A_V^l)(V_V^u - A_V^u) \right\} \log \left(\frac{\Lambda^2}{\mu^2} \right), \\ \delta F_a &= -\eta \frac{g^2}{48\pi^2 \Lambda^2} \left\{ \left[6G_A M_{f'}^2 - (G_V + G_A) Q^2 \right] (V_V^l + A_V^l)(V_V^u + A_V^u) \right. \\ &\quad \left. + \left[6G_A M_{f'}^2 + (G_V - G_A) Q^2 \right] (V_V^l - A_V^l)(V_V^u - A_V^u) \right\} \log \left(\frac{\Lambda^2}{\mu^2} \right), \end{aligned} \quad (10)$$

and to the t -channel,

$$\begin{aligned} \delta F_v &= \eta \frac{g^2}{12\pi^2 \Lambda^2} V_V^e \left[6G_A^i A_V^i M_{f'}^2 - (G_A^i A_V^i + G_V^i V_V^i) Q^2 \right] \log \left(\frac{\Lambda^2}{\mu^2} \right), \\ \delta F_a &= -\eta \frac{g^2}{12\pi^2 \Lambda^2} A_V^e \left[6G_A^i A_V^i M_{f'}^2 - (G_A^i A_V^i + G_V^i V_V^i) Q^2 \right] \log \left(\frac{\Lambda^2}{\mu^2} \right). \end{aligned} \quad (11)$$

Here, the indexes $u(l)$ denote the coupling constants associated to the upper (lower) vertices of Fig. 1 and the index i refer to the coupling constants of the internal fermion running in the loop, and e refers to the external fermion (*cf.* Fig. 2). The parameter μ corresponds to the characteristic energy scale of the physical process under consideration.

III. CONTRIBUTIONS TO Q_W

The one-loop contributions, δF_v and δF_a , are going to contribute to the APV in Cesium by modifying the coefficients of the Lagrangian that conventionally parametrizes the parity violating terms in the electron–nucleus interaction [11],

$$\mathcal{L}^{PV} = \frac{G_F}{\sqrt{2}} \left(C_{1u} \bar{e} \gamma^\mu \gamma^5 e \bar{u} \gamma_\mu u + C_{2u} \bar{e} \gamma^\mu e \bar{u} \gamma_\mu \gamma^5 u \right. \\ \left. + C_{1d} \bar{e} \gamma^\mu \gamma^5 e \bar{d} \gamma_\mu d + C_{2d} \bar{e} \gamma^\mu e \bar{d} \gamma_\mu \gamma^5 d + \dots \right) , \quad (12)$$

where the ellipsis represent heavy-quark terms $q = s, c, b, t$. In heavy atoms, as is the case of Cesium, coherence effects make the dominant source of parity violation to be proportional to the weak charge given by

$$Q_W = -2 [(2Z + N)C_{1u} + (Z + 2N)C_{1d}] , \quad (13)$$

where Z and N are the number of protons and neutrons in the atomic nucleus, respectively. So we only need to evaluate the one-loop effects of four fermion-contact interactions to the first and third terms in Eq. (12), neglecting all other contributions. Denoting the new physics contributions to C_{1q} by δC_{1q} , $q = u, d$, we can calculate the effect on $Q_W(^{133}_{55}Cs)$,

$$\Delta Q_W = -376 \delta C_{1u} - 422 \delta C_{1d} . \quad (14)$$

From the s -channel diagram corrections to the Zee vertex of the electron–nucleus interaction, it results that

$$\delta C_{1q} = \eta N_c \frac{g^2}{4\pi^2} (I_3^q - 2Q^q s_W^2) I_3^{f'} \left[(V_V^l + A_V^l)(V_V^u + A_V^u) + (V_V^l - A_V^l)(V_V^u - A_V^u) \right] \\ \times \left(\frac{M_{f'}}{\Lambda} \right)^2 \log \left(\frac{\Lambda}{\mu} \right)^2 , \quad (15)$$

and from the t -channel

$$\delta C_{1q} = \eta N_c \frac{g^2}{\pi^2} (I_3^q - 2Q^q s_W^2) I_3^{f'} (A_V^e A_V^{f'}) \left(\frac{M_{f'}}{\Lambda} \right)^2 \log \left(\frac{\Lambda}{\mu} \right)^2 . \quad (16)$$

From the s -channel corrections to the Zqq vertex we have

$$\delta C_{1q} = \eta N_c \frac{g^2}{4\pi^2} I_3^e I_3^{f'} \left[(V_V^l + A_V^l)(V_V^u + A_V^u) - (V_V^l - A_V^l)(V_V^u - A_V^u) \right] \\ \times \left(\frac{M_{f'}}{\Lambda} \right)^2 \log \left(\frac{\Lambda}{\mu} \right)^2 , \quad (17)$$

and from the t -channel

$$\delta C_{1q} = \eta N_c \frac{g^2}{\pi^2} I_3^e I_3^{f'} (V_V^q A_V^{f'}) \left(\frac{M_{f'}}{\Lambda} \right)^2 \log \left(\frac{\Lambda}{\mu} \right)^2 . \quad (18)$$

Here N_c denotes the color factor which depends on the number of quarks present in each graph. To get Eqs. (15)–(18) we have assumed $Q^2 = 0$. This is a reasonable assumption because the binding energy of the Cesium electron which is considered in the experiments (the outermost one) is of order of fractions of an electron-volt.

To proceed with our analysis, the first thing we must do is to choose the model or models for the four-fermion interactions. This is done by choosing the values of the constants η , g ,

V_V , and A_V in Eq. (7b). We are going to consider that the four-fermion interactions originate from fermion compositeness. Since the exchange of constituents among the fermions takes place in a strong interaction regime, we are led to consider $g^2 = 4\pi$ (see, e.g. Refs. [9,12]). In this case, the new physics scale, Λ , corresponds to the compositeness scale.

Initially, we estimate the contributions to ΔQ_W considering the present limits on the new physics scale for contact interactions involving two electrons and two other SM fermions [7,13,14]. We consider now only contributions to the Zee vertex (see Eqs. (15) and (16)) and assume the following choice of parameters,

$$(V_V^l + A_V^l)(V_V^u + A_V^u) + (V_V^l - A_V^l)(V_V^u - A_V^u) = 1 , \\ A_V^e A_V^{f'} = \frac{1}{4} . \quad (19)$$

With this choice the s - and t -channel contributions are equal. We note that such choice is very reasonable since it is similar to models like LL, RR, and others usually considered in the literature [7,12,14]. We assume such a model because what is really important for our estimates is only the order of magnitude of the couplings. In our calculations we take η so that the final contribution for Q_W is positive, since negative contributions are completely excluded. In Table I we have the value of ΔQ_W considering a b quark running in the loop, calculated separately for each possible quark in the nucleus and for the different channels, and for the sum of all contributions. We assumed $m_b = 4.5$ GeV, $\Lambda = 3$ TeV, and $\mu = m_e$, where m_e is the electron mass. The choice of the value of Λ was based on the results of Refs. [7,14]. We can see that the contributions are quite small because of the smallness of the b quark mass. In fact, because of the dependence on M_f^2 in Eqs. (15) and (16) we obtain even smaller results for lighter fermions in the loop. The results of the same calculation considering a t quark in the loop can be found in Table II. In this case we used $m_t = 175$ GeV, $\Lambda = 10$ TeV and $\mu = m_e$. The choice of the value of Λ was based on the results obtained in Ref. [7] which come from the constraints set by the very precise measurement of $\Gamma_{\ell\ell}$. In this case, the results we obtained are really very interesting. ΔQ_W is of the order of magnitude of the expected correction and even if we assume that the different contributions in the first two columns and rows of Table II interfere destructively instead of constructively, we have a result which falls into the interval in Eq. (6).

The absence of good limits on the compositeness scale of $qqq'q'$ interactions, involving at least one pair of heavy quarks, does not allow us to make for the Zqq vertex the same estimates we did for contributions to ΔQ_W from $eeqq$ interactions present in Zee vertex. What we can do is to determine bounds on the range of possible values of the compositeness scale compatible with Eq. (6). We assume that

$$(V_V^l + A_V^l)(V_V^u + A_V^u) - (V_V^l - A_V^l)(V_V^u - A_V^u) = 1 \quad \text{and} \quad V_V^q A_V^{f'} = \frac{1}{4} . \quad (20)$$

in Eqs. (17) and (18). This implies that the s - and t -channel contributions are equal. We choose η so that δC_{1u} and δC_{1d} are always negative, what implies $\delta C_{1u} = \delta C_{1d}$. Such assumptions allow us to get the most stringent bounds on Λ . In Tables III and IV we have, respectively, for a bottom and a top quark in the loop, the values of Λ which give the deviations expressed in Eq. (6) (we assumed $\mu = \Lambda_{QCD} \approx 300$ GeV). We evaluated Λ considering the contributions resulting from the u and d quarks present in the nucleus as

we did in Tables I and II. The results are shown to one and two channels contributing. The results in Table III show us that Q_W is reasonably sensitive to the presence of b quark loops. This implies that the presence of these loops can possibly explain the observed deviation in Q_W . As expected, Q_W is very sensitive to the presence of t quark loops, as can be seen from the results in Table IV.

It is worth mentioning that in the previous analysis it is reasonable to assume that the new physics scale, Λ , present in the s - and t -channel diagrams is the same, because the contact interactions come out of the exchange of the fermion constituents in a strong interaction regime. But, in the case we consider that massive bosons (e.g. leptoquarks and Z' 's) are responsible for the contact interaction, this generally is not a valid assumption. In fact, the s -channel diagram can be originated from the exchange of leptoquarks, diquarks or dileptons while the t -channel diagram from the exchange of ordinary massive gauge bosons, like a Z' associated to an extra $U(1)$ gauge symmetry. We are going now to consider some implications of the possible presence of these bosons.

We note that in the case of the most popular models for new massive vectorial bosons (W' , Z' and leptoquarks) the present bounds on their masses always satisfy the condition $M > 1$ TeV [13]. Based on this fact we assume, conservatively, the existence of four-fermion contact interactions with $\Lambda = 1$ TeV, and estimate the allowed values for the coupling constants. More exactly, what we do here is to estimate the allowed values of $g^2 \left[(V_V^l + A_V^l)(V_V^u + A_V^u) + (V_V^l - A_V^l)(V_V^u - A_V^u) \right]$, $g^2 \left(A_V^e A_V^{f'} \right)$, $g^2 \left[(V_V^l + A_V^l)(V_V^u + A_V^u) - (V_V^l - A_V^l)(V_V^u - A_V^u) \right]$ and $g^2 \left(V_V^q A_V^{f'} \right)$ in Eqs. (15)-(18). We denote these constants generically by G^2 . Considering that only δC_{1u} or δC_{1d} contributes to ΔQ_W , we obtained the results shown in Table V for f' being the top quark. We would get smaller allowed values in the case the contributions from the s - and t -channel were summed as well as if δC_{1u} and δC_{1d} contributed at the same time. Notice that the numbers in Table V are compatible with the coupling constants of the models in Ref. [13]. For other lighter fermions in the loops, the resulting coupling constants must be unacceptably large. For instance, for a b quark it should be of the order of 4π , as expected in the compositeness scenario.

IV. FINAL DISCUSSION AND CONCLUSIONS

In this article we investigated the one-loop effects arising from four-fermion contact interactions that do not appear in the Standard Model. We considered that no new physics contributes at the tree-level to the weak charge. This situation arises, for example, when the contributions from tree-level diagrams¹ interfere destructively (see, e.g. [15]). This allow us to consider that the new physics is in a sense universal, affecting all quarks and leptons and yet not contributing to Q_W at tree-level. Another possibility is that the new physics leads to negligible couplings among light quarks and leptons but sizeable ones in interactions involving heavy quarks.

¹Here we are concerned with diagrams involving the electron in the atom electrosphere and the u and d quarks in the nucleus. The effects arising from sea quarks are negligible.

We estimated the effects of the contact interactions on Q_W analyzing the contributions to the vectorial and axial form factors. We concluded that four-fermion interactions containing the top quark can lead to sizeable contributions through Zee and Zqq vertex, when fermion compositeness is assumed. Four-fermion interactions that contains the bottom quark can also lead to sizeable results through the Zqq vertex if the compositeness scale is in the range of few hundred GeV to 1 TeV.

The presence of new massive vectorial bosons, like Z' s and leptoquarks, can also explain the observed discrepancy in the measured value of the weak charge of Cesium. They contribute to Q_W only at the one-loop level, and can be parametrized by four-fermion contact interactions. In this scenario also the top quark loops are the responsible for sizeable contributions to Q_W . In fact, it is not surprising that Q_W is very sensitive to top quark loops; radiative corrections from the SM contributes with 1.3% of the value in Eq. (2).

We conclude by noting that in spite of the fact that our results are only approximate, for the very nature of the calculation of one-loop diagrams in effective interactions [16], we expect that the actual effects of new physics are not going to be far from what we have obtained. But we must be aware that cancellations among different one-loop diagrams may take place in actual theories, leading to non-observable effects. But our results suggest that one-loop effects of new physics may contribute significantly to the weak charge of Cesium, leading to the observed discrepancy between SM prediction and the experimental determination.

V. ACKNOWLEDGMENT

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TABLES

TABLE I. ΔQ_W for bottom quark in the loop.

Channel \ Quark	u	d	$u + d$
s	0.003	0.002	0.005
t	0.003	0.002	0.005
$s + t$	0.006	0.004	0.010

TABLE II. ΔQ_W for top quark in the loop.

Channel \ Quark	u	d	$u + d$
s	0.42	0.27	0.69
t	0.42	0.27	0.69
$s + t$	0.84	0.54	1.38

TABLE III. Limits on Λ , in GeV, for a bottom quark in the loop.

$\Delta Q_W \setminus$ Quark	u^a	d^a	$u + d^a$	u^b	d^b	$u + d^b$
0.28	540	580	810	780	830	1200
2.08	180	200	280	270	280	400

^aOnly one channel (s or t).

^bBoth channels.

TABLE IV. Limits on Λ , in TeV, for a top quark in the loop.

$\Delta Q_W \setminus$ Quark	u^a	d^a	$u + d^a$	u^b	d^b	$u + d^b$
0.28	26	28	38	37	40	55
2.08	9.0	9.6	13	13	14	19

^aOnly one channel (s or t).

^bBoth channels.

TABLE V. Limits on G^2 for contributions through the s -channel. For the t -channel divide the present values by 4.

$\Delta Q_W \setminus$ Quark	u^a	d^a	u^b	d^b
0.28	0.039	0.059	0.026	0.026
2.08	0.29	0.44	0.19	0.19

^aFrom contribution to the Zee vertex.

^bFrom contribution to the Zqq vertex.

FIGURES

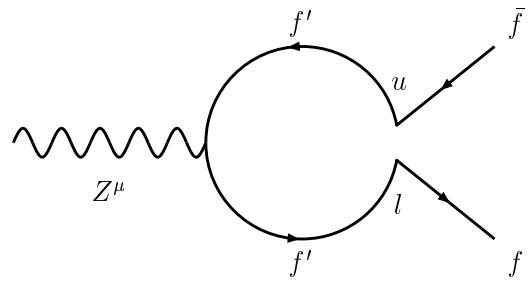


FIG. 1. *s*–channel diagram.

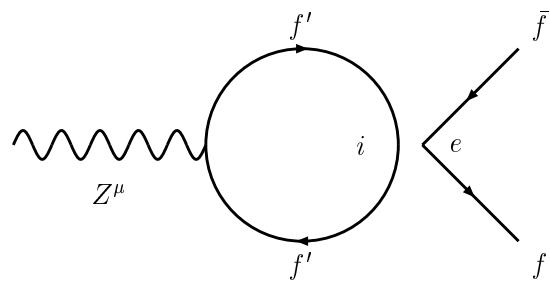


FIG. 2. *t*–channel diagram.